

A CRYOGENIC TEST STAND FOR LHC QUADRUPOLE MAGNETS

R. H. Carcagno, Y. Huang, D. F. Orris, T. J. Peterson, and R. J. Rabehl

Fermi National Accelerator Laboratory
Batavia, Illinois, 60510, USA

ABSTRACT

A new test stand for testing LHC interaction region (IR) quadrupole magnets at the Fermilab Magnet Test Facility has been designed and operated. The test stand uses a double bath system with a lambda plate to provide the magnet with a stagnant bath of pressurized He II at 1.9 K and 0.13 MPa. A cryostated magnet 0.91 m in diameter and up to 13 m in length can be accommodated. This paper describes the system design and operation. Issues related to both 4.5 K and 1.9 K operations and magnet quenching are highlighted. An overview of the data acquisition and cryogenics controls systems is also included.

INTRODUCTION

The U.S. contribution to CERN's future Large Hadron Collider (LHC) includes special high-gradient quadrupole magnets for focusing the particle beam at the LHC Interaction Regions (IR). Fermilab's Magnet Test Facility has the task of cold testing each of the U.S.-built high gradient IR quads and also testing some of the high gradient quads built by KEK in Japan. Tests must be done in 1.9 K, 0.13 MPa helium II, and the magnets must be powered up to about 13 kA.

A special cryogenic feed box and test stand are required for cooling and powering these large, 0.91 meter diameter by 7 or 13 meter long, quadrupoles. The concept for the feed can is based on Fermilab's Vertical Magnet Test Facility (VMTF) [1], which has successfully supported magnet tests since 1997. The feed can includes a lambda plate separating the normal and superfluid baths, a removable top plate carrying the power leads and instrument feedthroughs, a counterflow heat exchanger for precooling the 2 K supply, and an interface to the magnet that allows cold pipe connections with metal gaskets rather than welded joints, which are foreseen for the LHC tunnel. FIGURE 1 shows details of the feed can.

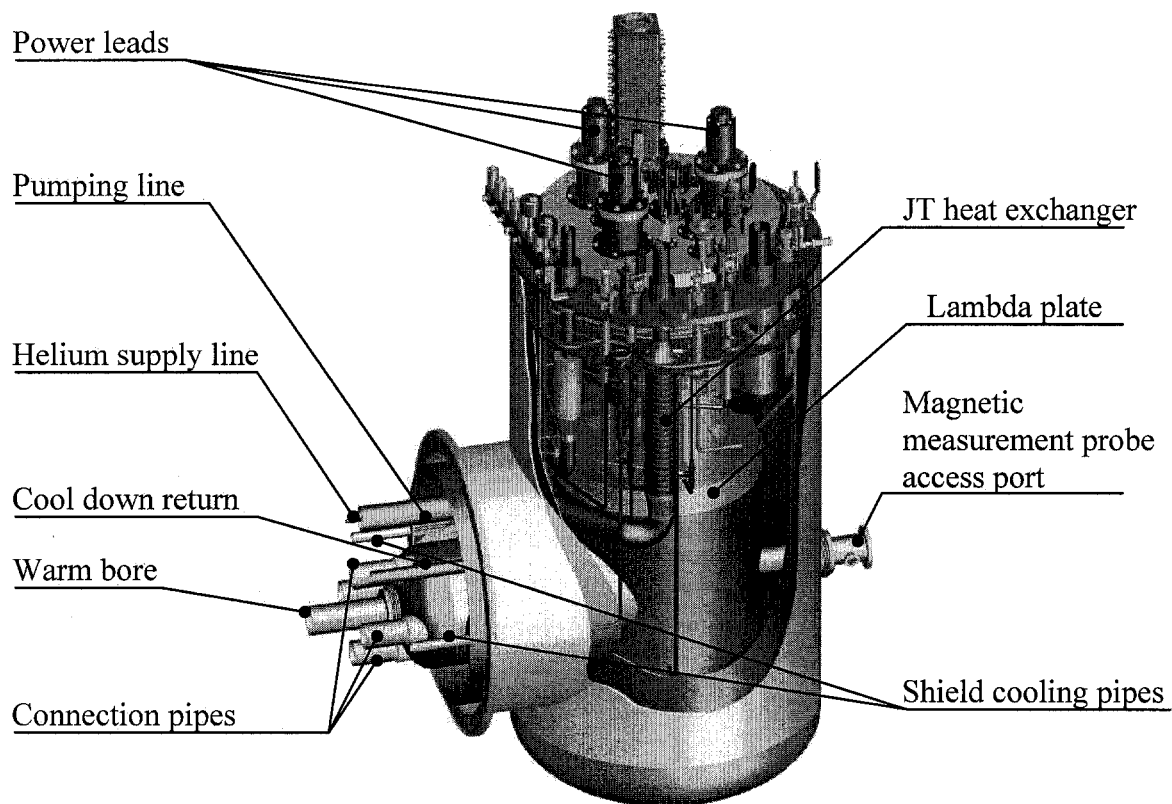


FIGURE 1. 3-D model of feed can showing details of interfaces to LHC quadrupole magnets.

To provide and maintain pressurized He II at 1.9 K, a He II heat exchanger [2-5] is required. The heat exchanger is the corrugated copper pipe built into the magnet cryostat for operation in the LHC. The LHC quadrupole magnet cold mass, corrugated He II heat exchanger, tubing, and feed can helium vessel are surrounded by a liquid nitrogen-cooled thermal shield and contained in a vacuum vessel [6]. The He II heat exchanger is located above and parallel to the magnet as shown in FIGURE 2. The heat exchanger shell side and bulk liquid helium within the magnet thermally communicate through a pipe 88.9 mm in diameter. Heat is transported from the magnet bath to the shell side of the heat exchanger via conduction through the liquid helium and then to saturated He II inside of a corrugated tube, where vaporized helium vapor is pumped away by the vacuum system.

The interconnect piping connections are made by aluminum seals coated with 0.127 mm (0.005 in) indium ribbon. Bare aluminum seals were initially used, but numerous leaks were encountered because of uneven clamping force provided by the chain clamps and the inability of the aluminum to fill small imperfections in the flange sealing surfaces.

LAMBDA PLATE INSERT DESIGN

The LHC IR quadrupole magnet test stand feed can at the Fermilab Magnet Test Facility uses a double bath of liquid helium. The 1.9 K bath is separated from the 4.5 K bath with a lambda plate. Similar to the lambda plate used in the VMTF, the feed can lambda plate is constructed from 50 mm thick G-10 plate. A type 304 stainless steel ring is bonded to the underside of the lambda plate and seals against a shoulder in the helium vessel. A mixture of Stycast 2850 (Emerson Cumming Company), catalyst 24LV, and

Cab-o-sil was applied to the helium vessel shoulder to create a low heat leak seal between the 1.9 K bath and the 4.5 K bath when the lambda plate is in place.

Like the VMTF lambda plate, the LHC IR quadrupole magnet test stand lambda plate can be removed from the feed can for repairs and modifications. One important difference is that the VMTF system uses the weight of the vertically oriented magnet to provide sealing force at the lambda plate. The new test stand accepts horizontal magnets, so an alternate method is required to provide the sealing force. This is accomplished using three tie-down rods. The tie-down rods pass through penetrations in the lambda plate and thread into gussets built into the helium vessel and, in conjunction with a shoulder machined into each rod, provide clamping force on the lambda plate. The warm ends of these tie-down rods pass through the feed can top plate and allow the lambda plate to be removed from the feed can as part of an insert, which includes the top plate, closed-cell foam baffles, and a liquid nitrogen-cooled baffle shield.

OPERATIONAL RESULTS

Cool-down from 300 K to 4.5 K

FIGURE 2 shows a simplified flow schematic for the cryogenic test stand. To begin cooling down from 300 K, liquid helium is supplied through control valve V1. The liquid and cold gas flow to the far end of the test stand through cooling holes in the cold masses and return to compressor suction through the cool down return line and valve V2. A small amount of cold gas is also taken through control valve V3 to begin cooling the magnet heat exchanger. Once the cool down return line reaches liquid helium temperature, valve V2 is closed and liquid begins to accumulate in the feed can. Control valve V1 is closed when the liquid level reaches the lambda plate, and control valve V4 is used to raise the liquid level above the lambda plate to the normal operating level. Boil-off is taken through the vapor cooled 15 kA power leads or the bypass control valve V5. Thirty-four hours of active cooling are required, to cool an LHC Q2a&b magnet to 4.5 K with a flow rate of 7 g/s.

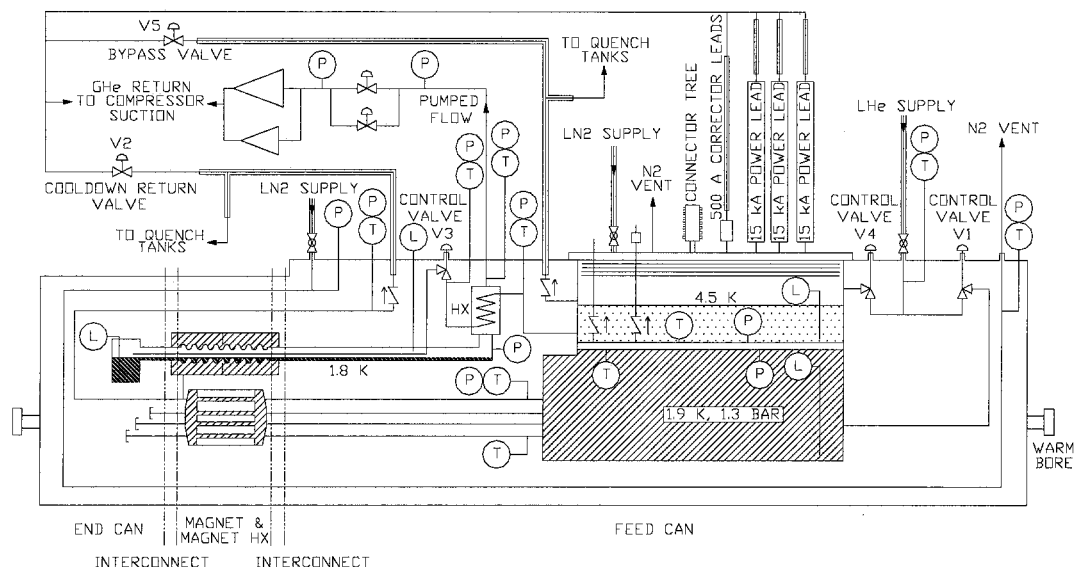


FIGURE 2. Simplified flow schematic for the cryogenic test stand.

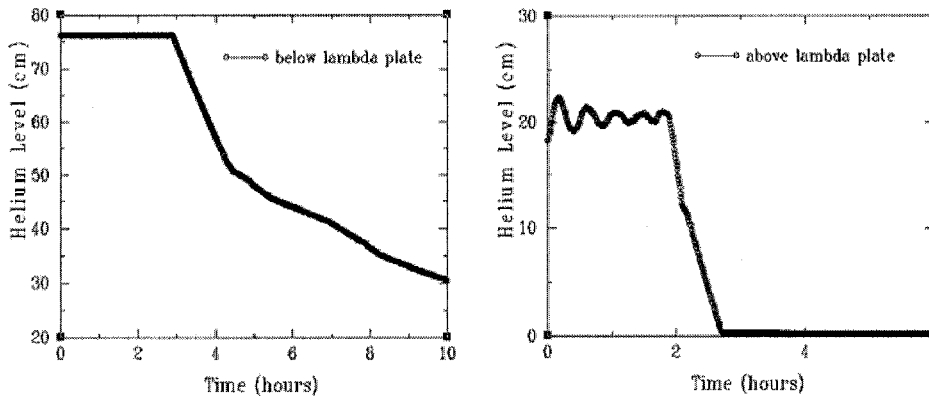


FIGURE 3. Boil off test at 4.5 K. The left plot shows liquid level below the lambda plate. The change in slope occurs where the liquid level reaches the top of the helium vessel snout. The right plot shows liquid level above the lambda plate. The change in slope on this plot occurs at the tip of the power leads.

Thermal Performance at 4.5 K

FIGURE 3 shows boil-off test results at 4.5 K. Both liquid helium supply valves V1 and V4 are closed, and vaporized helium vapor is taken through the vapor cooled 15 kA power leads and the bypass control valve V5. The slope on the helium level curve below the lambda plate is used to estimate the total heat leak to the 4.5 K environment. Sources of heat leak include heat conduction through the magnet support structure and down the helium vessel wall, radiation from the thermal shield, and a combination of conduction and radiation from the magnetic measurements warm bore.

A “warm bore”, an anti-cryostat, allows room temperature magnet measurement probes to measure the magnetic field in the magnet bore while the magnet is cold. During some phases of testing, when magnetic measurements are not required, the warm bore may be evacuated and allowed to passively cool, reducing the heat load to the 2 K temperature level in the magnet. When operating at 4.5 K, the estimated heat load below the lambda plate is 55 W when the warm bore is at room temperature.

Quench Performance at 4.5 K

FIGURE 4 shows the pressure and temperature responses following a 7 kA heater-induced quench at 4.5 K. After a 4.5 K quench, the system is ready to test within 30 minutes.

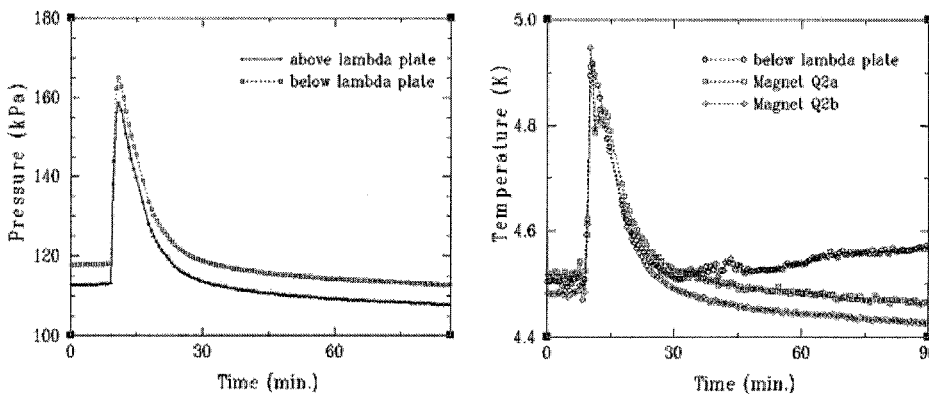


FIGURE 4. Pressure and temperature responses following an LHC Q2a 7 kA heater-induced quench at 4.5 K.

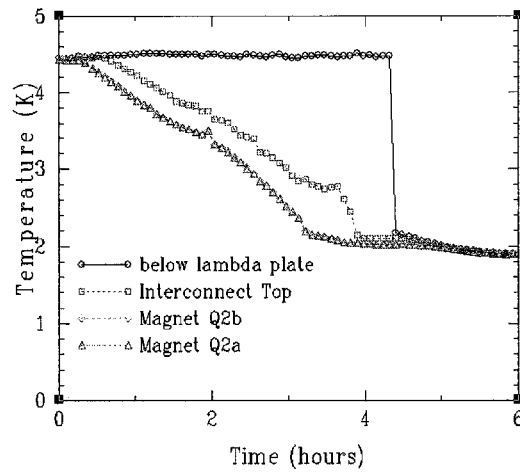


FIGURE 5. Cryogenic test stand cool down from 4.5 K to 1.9 K.

Cool-down from 4.5 K to 1.9 K

Liquid helium, at approximately 4.5 K and 1.3 bar, flows from above the lambda plate, into the tube side of the counter-flow heat exchanger where it is cooled to superfluid temperatures and then is taken through control valve V3 to expand. The two-phase mixture is supplied to the overflow vessel at the return end of the magnet. As liquid accumulates in the overflow vessel, it begins spilling into the horizontal heat exchanger pipe. The surface of the horizontal heat exchanger pipe becomes wetted, and heat is transferred from the magnet bath to this saturated 1.9 K liquid. Generated vapor passes through the shell side of the counter-flow heat exchanger and is pumped away by two parallel vacuum pump skids. The larger skid has a Kinney KMBD-3201 oil-injected Roots blower backed by a Kinney KLRC-950S liquid ring pump. The smaller skid has a Kinney KMBD-2002 oil-injected Roots blower backed by a Kinney KLRC-525 liquid ring pump. The combined capacity of the two pumping skids is 3.9 g/s at an inlet pressure of 16 mbar.

Approximately five hours are required to cool an LHC Q2a&b magnet from 4.5 K to 1.9 K as shown in FIGURE 5. The actual time required depends on how well the liquid level in the overflow vessel is maintained. The optimum liquid level to maintain appears to be around 52.8 cm (20.8 in). At about 53.3 cm (21 in), liquid droplets become entrained in the pumped vapor flow. This increases the liquid usage rate and slows the cool-down rate.

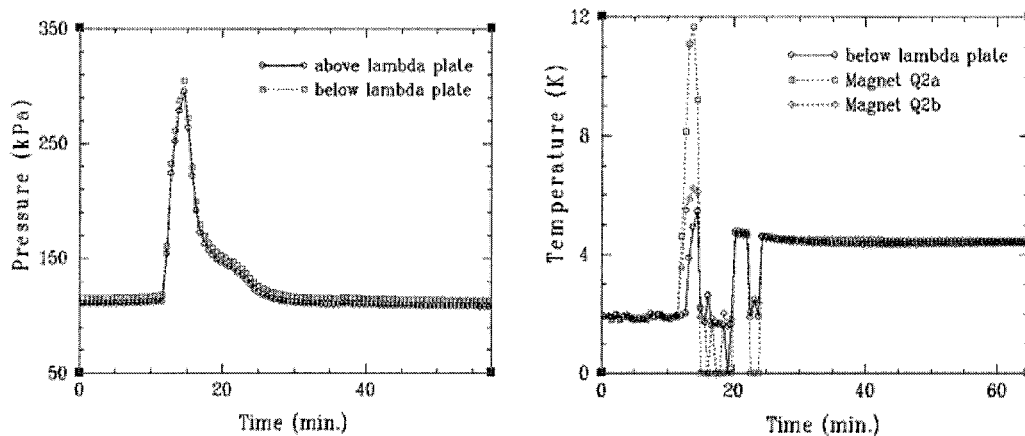


FIGURE 6. Pressure and temperature responses following an LHC Q2a 12.9 kA quench at 1.9 K.

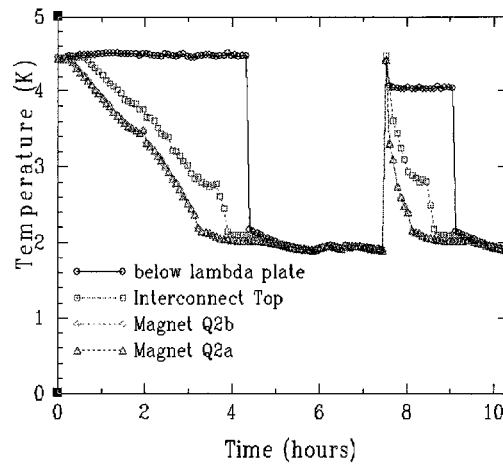


FIGURE 7. Cryogenic test stand recovery to 1.9 K after a Q2b quench at 11.1 kA.

Quench Performance at 1.9 K

FIGURE 6 shows the pressure and temperature responses following a 12.9 kA quench of the Q2b cold mass. FIGURE 7 shows that the recovery time required for this typical quench is about three hours before the system is ready for the next test.

When a magnet quenches or is tripped, some of the stored energy of the magnet coils is deposited in the surrounding helium. An external dump resistor is often used to dissipate approximately half of the stored energy. The resulting pressure and temperature rises will depend not only on the magnet quench current but also on whether an external dump resistor is used. The most violent tests conducted on this test stand power the two cold masses of an LHC Q2 magnet at 1.9 K to 13 kA before tripping them. A dump resistor is not used, so all of the stored energy is deposited in the helium. The feed can pressure quickly rises to 0.48 MPa (70 psia) where the system pressure relief valve opens.

TEST STAND CONTROL SYSTEM

The test stand control system follows the architecture of the Magnet Test Facility (MTF) 1500 W refrigerator control system [7]. However, the test stand control system is a completely independent module, with a separate programmable logic controller (PLC) and supervisory control and data acquisition (SCADA) node. Therefore, any failure of this system does not affect the refrigerator operability. The test stand control system is also completely independent from the test stand data acquisition (DAQ) and quench management systems, which is important in order to maintain cryogenic operability of the test stand in the event of reconfiguration or failures of these systems. Operators can bring up test stand operator displays from any operator station, so they can easily navigate between refrigerator control displays and test stand control displays. Real-time and historical trending is available. An alarm management system and first-fault diagnostics logic helps to quickly identify and troubleshoot problems. A software link allows two-way communication between the test stand control system database and the DAQ system, and an integrated pager system provides remote notification of alarm conditions to operators. TABLE 1 shows hardware and software components of this industrial control system.

TABLE 1. Test Stand Process Control System.

Sub-System	Choice
Programmable Logic Controller (PLC)	Siemens 505-454 PLC
Input/Output (I/O) Cards	Siemens 505 series
Control Network	Ethernet with TCP/IP in a routed network
PLC Programming Language	FasTrak 505 WorkShop
Operator Interface Software	FIX32 from GE/Intellution
Electrical Loops	24 VDC for discrete I/O, 4-20 mA or 0-5 VDC for analog I/O.
Temperature sensors	Lakeshore CERNOX RTDs with Model 234 temperature transmitter cards and Pt RTDs with Model 231P cards.
Liquid Helium Level Probes	American Magnetics superconducting level sensors and Model 135 liquid helium level monitor
External Interface	ODBC interface to FIX32 real-time database

TEST STAND DAQ SYSTEM

The test stand DAQ system follows the standard MTF DAQ architecture. Its main function is to provide accurate 4-wire measurements of devices such as temperature sensors and strain gauges. Fast sampling of these devices is not typically required, so this system is designed for relatively low sampling frequency (~ 8 Channels/sec). As an example of the DAQ system accuracy, assuming that all temperature sensors in a current chain are at around 4.5 K the absolute measurement error introduced by the DAQ system is approximately ± 4 mK. Details of the DAQ system have been described elsewhere [8].

TEST STAND QUENCH MANAGEMENT SYSTEM

The quench management system performs the following tasks: it monitors/controls the magnet protection hardware, which includes the magnet heater power and the dump extraction resistor; provides permits to the power system to turn on; and it monitors the magnet for the onslaught of resistive voltages (quench detection) [9]. In the event of a quench, it carries out the necessary actions in order to shut down the power supplies and extract the energy from the magnet while logging magnet voltage data at a fast rate in order to characterize the quench. The quench management signals have been standardized so this system can be easily multiplexed to several test stands.

TEST STAND CONFIGURATION FOR LHC MAGNETS

In order to perform power tests of the LHC magnets the test stand must be capable of supplying the required current as well as a means for extracting energy from the magnet in the event of a quench. Since the LHC Q2 magnets have two cold masses in the same cryostat, provisions must be made to power and protect all three possible magnet test configurations: Q2a only; Q2b only; or, Q2a & Q2b in series. The test stand current bus and quench protection controls have been designed to accommodate any of these configurations without having to thermal cycle the magnet or modify the quench protection hardware. This is accomplished via the use of three helium cooled power leads in the feed can. These power leads are connected to the magnets' superconducting leads such that any magnet configuration can be powered by choosing the correct power lead pair. CERN

modified heater firing units (HFUs) are cabled to power the strip heaters on both cold masses, which are always protected due to a hardwired voltage configuration / protection scheme that inherently protects all possible power configurations.

CONCLUSIONS

The cryogenic system for testing the LHC interaction region high gradient quadrupole magnets at temperatures from 4.5 K to 1.9 K has been successfully commissioned at Fermilab and has been operational since 2001. The system can be cooled down to 4.5 K from room temperature in 34 hours and to 1.9 K in another 5 hours. The test stand includes three conventional, vapor cooled power leads for electric power capability up to 15 kA.

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